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GRADES AND OTHER LOADS EFFECTS ON ON-ROAD EMISSIONS: AN ON-BOARD ANALYZER STUDY

By

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Abstract

This ongoing project was developed to assess driving patterns likely to promote emission excursions greater than those encountered in current dynamometer driving cycles, using an instrumented vehicle equipped for on-road testing on hills. The vehicle is equipped with an on-board data-logger and analyzers for hydrocarbons and carbon monoxide, along with sensors for basic driving parameters such as speed, manifold pressure, throttle position, and grade. The on-board emission instrumentation was compared to dynamometer tests by performing parallel sampling. The results presented high correlation among emission rates: CO (R^2=0.82), Hydrocarbons (R^2=0.72).

Controlled runs with predetermined cruises and accelerations were conducted on flat terrain and hills on grades ranging from 0% to 7%. The hills were located in metropolitan Los Angeles, both on freeways and arterials. As a reference, the EMFAC7F speed correction factors (SCF) were used to calculate the corresponding emission rates using the flat terrain emissions. When driving on grades above 3%, the hydrocarbons emissions were above the emissions rates calculated using the SCFs 86% of the time. In the case of CO, while driving on grades greater than 3%, all emission rates were higher than those predicted from the SCFs. While driving on negative grades or flat terrain emission rates were closer to the SCFs estimates. For hydrocarbons the effects are on the order of 0.04 g/mile per 1% grade increment. The case of CO was more dramatic with a predicted increase for a 1% grade increment of 3.0 g/mile. The results have important uncertainties (R2=0.40 for hydrocarbons and R2=0.36 for CO) since there is evidence of a synergistic effect of grade and speed, and a potential load threshold for emission excursions.

Effects on engine total load, such as passengers or air conditioning, may also be important. On the average the emission effects are exacerbated with a fully occupied vehicle (4 passengers) while driving on a hill (4.5% grade) by a factor of 2, both for hydrocarbons and CO. For air conditioning operation, tests were performed on two hills (4.5 and 6.7%). The emission rates of hydrocarbons showed an increase of 57% when air conditioning at a maximum setting was used. For CO the increase was 268% for air conditioning operation.

The results highlight the importance of including emissions caused by grades in the emission inventory. This study has also significant implications for assessing the effectiveness of some transportation measurements.

Introduction

The California Air Resources Board (CARB) has been concerned with the lack of available information on motor vehicle emissions occurring while driving a vehicle on grades. The United States Environmental Protection Agency (EPA) stated in its Federal Test Procedure (FTP) review project[1] that "the nationwide vehicle-miles traveled weighted average for road gradient" is 1.6%. This figure assumes that the up grade miles are equal to the down grade miles. A number of recent studies have been addressing the issue of driving on positive gradients, namely in hills, tunnels or unspecified roads.

Kelly and Groblicki[2] used a GM Bonneville SSE to assess real-world emissions. They observed that during enriched operation, carbon monoxide (CO) and hydrocarbons instantaneous emissions increased by a factor of 2500 and 40 respectively, relative to stoichiometric operation. The average peak time-based emission increases were reported at 4 g/s for CO and 0.024 g/s for hydrocarbons, while nitrogen oxides (NO_x) emissions did not increase substantially. Some of these enriched operating modes occurred while driving Kellogg Hill on the San Bernardino Freeway (I-10), which has grades of 5%. In some cases, the cumulative emissions experienced by enrichment operation due to the grade were more than 10 times greater than the cumulative emissions experienced during a cold start for CO. For hydrocarbons the cumulative emissions due to the grade were on the same order as cold start cumulative emissions .

Researchers from the University of California Los Angeles (UCLA)[3] in a similar study established that driving the Sepulveda Hill on the San Diego Freeway (I-405), which has a grade of 4%, open-loop operation was promoted at least 20 times more than during generic freeway driving. In a later report[4] the UCLA researchers estimated the emissions due to open-loop operation. The hill would promote 10 times more emissions for CO, 3 times more emissions for hydrocarbons, and 5 times more emissions for NO_x relative to flat terrain.

A preliminary assessment on grade effects was performed by EPA[5], simulating a constant 2% positive grade on a dynamometer. The emission increases due to grade were 42% for hydrocarbons and NO_x, and 80% for CO. These translate in incremental increases of 3.2 g/mile for CO, 0.11 g/mile for NO_x, and 0.05 g/mile for hydrocarbons. In this study, the effects of air conditioning also were assessed. The emission increases due to air conditioning were 26% for hydrocarbons, 56% for CO and 78% for NO_x.

Studies conducted in Australia[6] regarding modeling and measurements of mobile source emissions near arterial roads, also addressed the issue of grades. The emissions were predicted using a load based model and accounted for measurements in flat terrain, 0.9% grades and 1.7% grades. Although no conclusive data were presented the research team considered "that the effect of slope is dramatic....resulting in increased carbon dioxide (CO_2) and NO_x emission rates but with smaller influence on CO and hydrocarbon emission rates."

A recent study conducted in the Fort McHenry Tunnel[7], which has a positive grade of 3.76%, assessed that the effect of this grade was found to be a factor of 2 in terms of g/mile emissions when compared to equivalent negative grade emission rates.

The main objective of this study is to provide additional information on emission rates observed during high engine loads, emphasizing the variation that may occur on different road grades, in order to facilitate the evaluation of a more accurate mobile source emission inventory.

Vehicle, On-Board Data Acquisition System, and Parameters

The CARB has a vehicle for on-road testing instrumented by Sierra Research[8]. The vehicle is a 1991 GM Lumina, with a 3.1 liter engine, port fuel injection, exhaust gas recirculation, a 3 way catalyst, with an odometer reading of 18441 miles as October 15, 1994 and a nominal inertia weight of 3625 lb. The vehicle is equipped with a on-board data acquisition system that monitors engine and vehicle dynamic parameters as well as exhaust gases. Figure 1 presents the vehicle instrumentation layout. In Table 1, the parameters recorded from the Electronic Control Unit (ECU) or other sensors are presented. These are manifold absolute pressure, O2 sensor, throttle position, engine speed, coolant temperature, manifold temperature, and vehicle speed. Two accelerometers are added on and mounted near the center of gravity of the vehicle, one longitudinally and the other

laterally. These two signals coupled with vehicle speed are used to assess the grade of the road. Sampling time is recorded from the computer's internal clock. The on-board analyzer (MPSI, Model

PGA-9000) measures concentration of hydrocarbons, carbon monoxide, carbon dioxide and oxygen in the exhaust and calculates the air to fuel ratio.

Road grade angle, was calculated in real time with the aide of accelerometers. The accelerometers act as a pendulum and sense the total acceleration to which a vehicle is subjected. By removing the acceleration component due to change in speed from the total acceleration, it is possible to estimate the gravitational component. Once grade is known, the main components of the load experience by the vehicle engine may be calculated. The total driving energy[9,10] (equal to power for one second intervals) requirements for vehicle motion may be expressed as:

$$\Delta E_T = \Delta E_K + \Delta E_{RLa} + \Delta E_G + \Delta E_{OL}$$

where

ΔE_T = total change in energy/work in one second,
ΔE_K = change in kinetic energy,
ΔE_{RLa} = change in road load resistance (approximated),
ΔE_G = change in grade resistance,
ΔE_{OL} = change in other loads, such as air conditioning, lights, etc.,

The exhaust volume and mass from the test vehicle was calculated using the method developed by DiGenova et al.[8]

Parallel Sampling On-Dynamometer

The calibration of the on-board emission instrumentation was performed by parallel sampling on a dynamometer with second-by-second emissions capability. In this phase, additional calibration was performed on the speed sensor as compared to the dynamometer calculated speed from the rollers revolutions. The calibration phase consisted of different driving cycles including some with high load/high acceleration events. All the dynamometer tests were performed in CARB's Haagen-Smit Laboratory (HSL), located in El Monte, California, which has been in operation at its present site since 1972. Testing on the dynamometer provided two streams of data, one integrated from the sampling bags and the modal, second by second data. Both streams were intercompared as integrated and summarized data. The on-board data acquisition system also provided integrated summaries. The results were intercompared from the three integrated streams: bag, modal, and on-board. After finding the specific relationship between CVS measurements and on-board measurements, all on-board collected data was corrected using regression to reflect emissions equivalent to the CVS unit.

Grade Measurements

Since grade effects on vehicle emissions were the primary research concern in this study, an effort was made to select roads that were safe and drivable, and that had a range in slopes from near zero to, if possible, 10%. The scope of the study was to define the emissions over a wide driving domain, regardless of the frequency of such events in terms of activity. A protocol was developed to drive each route that included: warming time to prevent cold starts, waiting time before the route was driven; target speeds, target accelerations; and safety requirements. An analysis of the potential driving routes within the SoCAB was performed. Initial screening of main highways and arterials with inclines were performed on a 1:250000 scale topographic map. Once prospective test sites were identified, a secondary assessment of the road grades was performed on 1:24000 scale topographic maps. A follow up site survey for safety and suitability was subsequently conducted. Once the route was selected, a detail grade profile was developed using the 1:24000 scale topographic maps. Average and maximum grade and easily identifiable markers, such as, intersections, were found. To provide a baseline and a readily accessible route, a circuit was defined adjacent to the HSL in El Monte which has a nominal grade of zero and a length of 1.18 miles. Additionally, a long flat strip was identified on Highway 58 near Barstow, with a nominal grade of less than 0.3%. This strip was used to drive at constant speeds and at targeted accelerations, including wide open throttle.

The selected roads with grades included Montebello (FWY 60), Kellogg Hill (FWY10), Sepulveda Hill (FWY405), Colima Hill (in Whittier), Crenshaw (in Palos Verdes), and Las Tunas Canyon (in Malibu). Driving on the hills was primarily composed of constant speeds at targeted low accelerations. Three nominal speeds were tested per hill, these nominal speeds were 35, 45 and 55 mph. The final run was designed to follow the general car flow on the road. A summary of the driving routes is presented in Table 2, the hill profiles are presented in Figure 2.

Parallel Dynamometer Testing

The calibration of the on-board emission instrumentation was performed by parallel sampling on a dynamometer with second-by-second emissions capability. This procedure was performed to relate on-road collected data with dynamometer collected data. A summary of the parallel testing is presented in Table 3. A correlation coefficient higher than 0.99 was observed when the on-board speed sensor was compared to the speed calculated from the dynamometer roller revolutions**.**

The on-board collected data generally had higher emission rates compared to the CVS bag collected data. The correlation coefficients are in good agreement when the extremely high demand ACCEL1 cycle was censored. CO presented a correlation coefficient of 0.82, having a multiplicative factor of 0.739 to adjust to CVS signal. Hydrocarbons presented a lower correlation coefficient of 0.72 and a value of 0.311 to adjust the on-board signal to the CVS signal.

On-Road Testing

Grade. Figures 3 and 4 show an example of the instantaneous emissions while driving up and downhill. The "hill" is actually Agua Negra Canyon in Crenshaw Boulevard, at the Palos Verdes Peninsula. It has a maximum relative elevation of 420 feet (860 feet above sea level) and a grade of 6.7%. Three tests are presented with running speeds of 32, 38 and 43 mph. The additional emissions imposed by the positive grade compared to the downhill fraction are evident, even for the low speed tests, for hydrocarbons. The effects on carbon monoxide are very dramatic for the higher speed run, showing typical open-loop or enrichment behavior[12].

To analyze the effects of different grades, each run was desegregated into idle (less than 5 mph), driving on flat terrain (less than ±0.5% grade), positive grade, and negative grade. For each category the relevant statistics on the dynamic and emission parameters were calculated, such as duration, distance, average and maximum speed, total load, and distance and time based emission rates. Figure 5 and 6 present the time based emission rates of hydrocarbons and CO compared to grade. As in the instantaneous emission case the effect of grade is evident, exacerbated by high speeds. Also, emission increases were triggered for grades above 4%.

As a reference, the EMFAC7F speed correction factors (SCF)[13] were used to calculate the corresponding emission rates using the flat terrain emissions. Figure 7 and 8 presents the distance based emission rates for hydrocarbons and CO. When driving on grades above 3%, the hydrocarbons emissions were above the emissions rates calculated emissions using the SCF 86% of the time. In the case of CO, while driving on grades greater than 3%, all emission rates were higher than those predicted from the SCFs. Emission rates while driving on negative grades or flat terrain were closer to the SCF estimates.

The impact of speed and grade on emission rates was evaluated using multiple regression on the positive grade fraction of each run, the results are presented in Table 4. For hydrocarbons the effects are on the order of 0.04 g/mile per 1% grade increment, a tenth of the current California emission standard for passenger vehicles. The case of CO was more dramatic with a predicted increase for a 1% grade increment of 3.0 g/mile, slightly less than half of the current California standard. The results have important uncertainties (R^2=0.40 for hydrocarbons and R^2=0.36 for CO) since there is evidence of a synergistic effect of grade and speed, and a potential load threshold for emission excursions.

Figures 9 and 10 present the emission rates for hydrocarbons and CO as a funcion of the average total load, calculated using Equation (4). An important fraction of the emissions are exacerbated when average loads exceeded 30 HP. A follow up study in this area will require analyzing the instantaneous data set to describe emission rates in probabilistic terms and instantaneous loads.

Additional Effects, Commuters / Passengers and Air Conditioning. A commuter car was simulated on a hill with passenger loads of one to four passengers. Each passenger load was driven at three different nominal speeds. In a similar fashion air conditioning effects were tested using three nominal speeds for no air-conditioning operation and for air-conditioning operation at maximum setting.

The air conditioning effect test was conducted on two hills. The experiments were designed to identify the magnitude of additional loads.

This study was not able to detect differences on the emission rates for passenger loads of one to three passengers at three different speeds. In some cases the emissions with one passenger were higher than with two or three passengers on a single hill. Nevertheless the inclusion of a fourth passenger triggered emissions particularly at high speeds. In fact, for this particular run (4 passengers, speed of 51 mph) the positive kinetic energy was slightly higher (18%) than the average of the three previous runs, as well as the load due to grade (8% higher). At this moment is difficult to desegregate one effect from the other. On the average the effects are exacerbated with a fully occupied vehicle both for hydrocarbons and CO by a factor of 2 on a positive 4.5% grade.

For air conditioning operation, tests were performed at three speeds and two positive grades (4.5 and 6.7%). The analysis included the positive grade fraction of the runs. The distance based emission rates of hydrocarbons showed an increase of 57% when air conditioning at a maximum setting was used. For CO the increase was 268% for air conditioning operation. Results for commuters/passengers and air conditioning effects are presented on Table 5.

Conclusions

The results highlight the importance of including emissions caused by grades in the emission inventory, particularly in areas where topography imposes road grades of approximately 4% or greater. In addition, these effects are exacerbated when air conditioning is operating or a fully occupied vehicle is used. It was very interesting to find a potential total load threshold around 30 HP both for hydrocarbons and CO. Using the current information, the total data set should be analyzed in terms of the instantaneous emission rate distributions and their potential predictors such as: grade, speed or loads. In some cases the conflicting results showed the importance of approaching the analysis in a probabilistic manner, rather than in a deterministic way.

Potential follow up analyses include the geographical assessment on the grade distribution using current technology of geographic information systems (GIS). Additionally, an assessment of the load distributions on the data of the instrumented fleets studies[1,3] will facilitate a refinement of the current emission inventory. It is important to remember that the study was performed on a single, modern technology vehicle. We believe that the current results may be applied in a relative fashion, cautioning the use of absolute values. These results also may have significant implications for current efforts to more reliably model the efficacy of certain transportation control measurements.

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Disclaimer

The contents of this paper/report and the authors' findings do not necessarily reflect the views and policies of the California Air Resources Board. The mention of contractors and commercial products is not to be constructed as either an actual or implied endorsement of such individual products.

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Table 1. Basic parameters measured by the On-Board Data Acquisition System

Measured		Postprocessed	
Manifold Absolute Pressure	kPa	Run Time	s
O_2 Sensor	V	Grade	%
Throttle Position	V	Exhaust-Mass	g
Engine Speed	rpm	HC	mg
Coolant Temperature	V	CO_2	g
Manifold Absolute Temperature	V	CO	g
Vehicle Speed	MPH	A/F Calculated	ratio
Longitudinal Acceleration	G's	Fuel Economy	MPG
Lateral Acceleration	G'S		
Time from Midnight	s		
Hydrocarbons	ppm		
CO_2	%		
CO	%		
O_2	%		
A/F Analogic Signal	ratio		

Table 2. Driving routes.

Number	Location	Grade percent	Elevation Change feet
1	Telstar Avenue in El Monte	≈0	0
2	Highway 58 near Barstow	<0.3	20
3	Montebello Hill Freeway 60	2	160
4	Sepulveda Hill Freeway I-405	3.5	620
5	Kellogg Hill Freeway I-10	4.3	330
6	Colima Hill in Whittier	4.5	100
7	Crenshaw Canyon in Palos Verdes	6.7	420
8	Tuna Canyon in Malibu	11	1350

Table 3. Parallel dynamometer sampling. Integrated samples of the CVS unit and the integrated samples of the on-board instrumentation were used.

Parameter	Descriptor	Linear Regression y = mx+b x = on-board y = bag	Linear Regression, forced to 0 y = mx x = on-board y = bag
Hydrocarbons			
	R	0.855	0.851
	R^2	0.731	0.724
	b	-0.006	-------------
	p-value of b	0.711	-------------
	m	0.343	0.311
	p-value of m	<0.01	<0.01
	n	8	8
CO			
	R	0.907	0.907
	R^2	0.823	0.823
	b	0.060	-------------
	p-value of b	0.921	-------------
	m	0.726	0.739
	p-value of m	<0.01	<0.01
	n	8	8

Table 4. Estimated impact of speed and grade on emission rates using regression. The data points correspond to the positive grade fraction of the run.

Emisssion Rate = $a_0 + a_1$* Speed + a_2*Grade

		HC/s	CO/s	HC/mile	CO/mile
	R	0.668	0.616	0.635	0.603
	R^2	0.446	0.379	0.403	0.364
	a_0	-0.00494	-0.70833	-0.31338	-49.35373
	p-a_0	0.003	0.002	0.022	0.004
Speed	a_1	0.00011	0.01687	0.00689	1.17734
	p-a_1	0.002	0.001	0.018	0.001
Grade	a_2	0.00049	0.03827	0.04283	2.99567
	p-a_2	0.001	0.048	0.001	0.037
	n	29	29	29	29

Table 5. Estimated impact of passenger load and air conditioning on emission rates. For passenger load the test was performed at three speeds and a grade of 4.5%. For air conditioning operation the test was performed at three speeds and two grades (4.5 and 6.7%). The data points corresponded to the positive grade fraction of the run.

		HC/s	CO/s	HC/mile	CO/mile
Passenger load					
	1, 2 & 3 passengers	0.0010	0.173	0.08	13.4
	4 passengers	0.0021	0.345	0.16	25.3
	increase	105%	100%	96%	89%
A/C					
	off	0.0023	0.190	0.20	15.0
	on	0.0038	0.703	0.31	55.2
	Increase	68%	269%	57%	268%

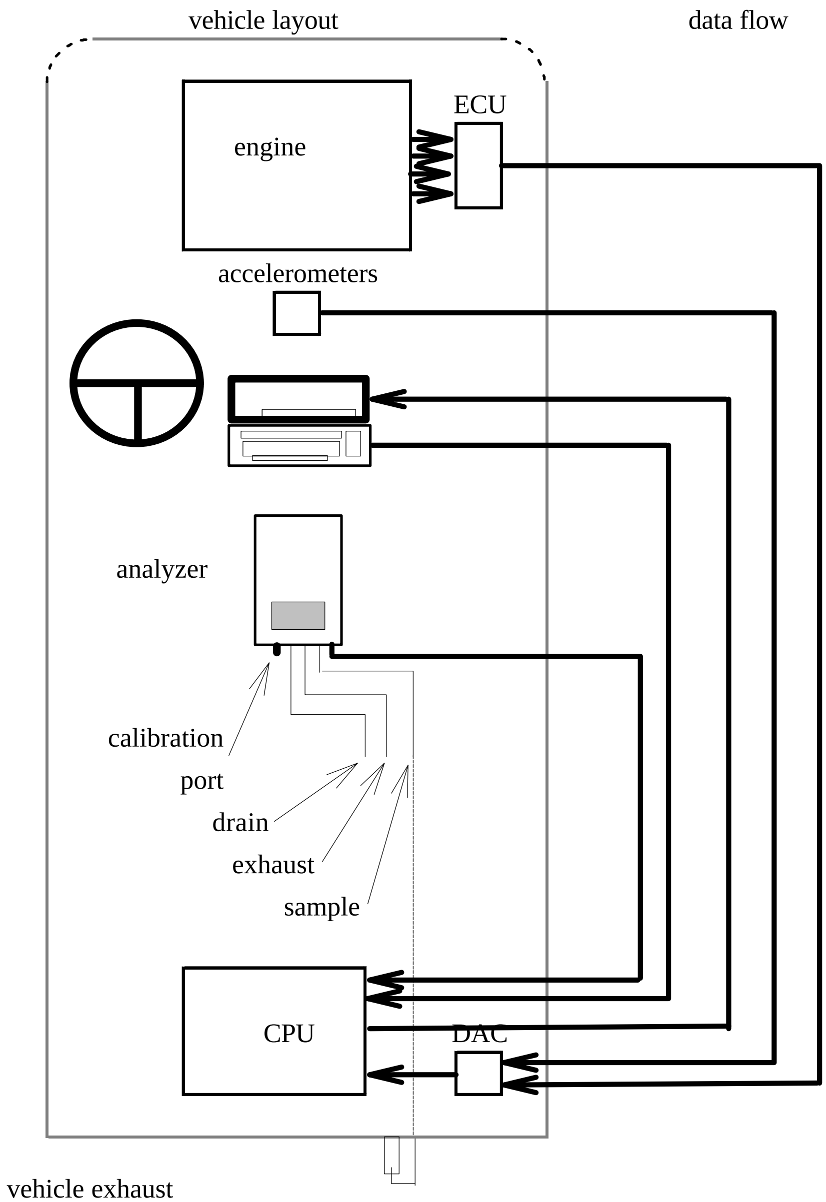
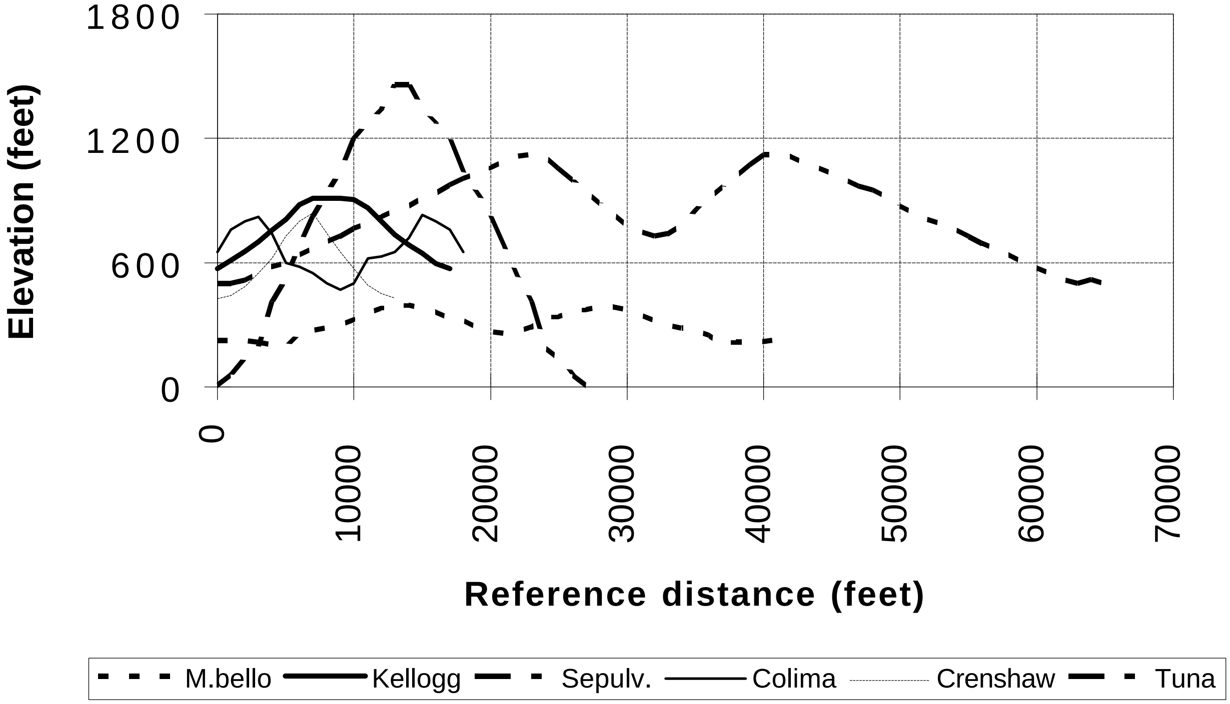


Figure 1. Vehicle instrumentation diagram

Figure 2. HILL PROFILES



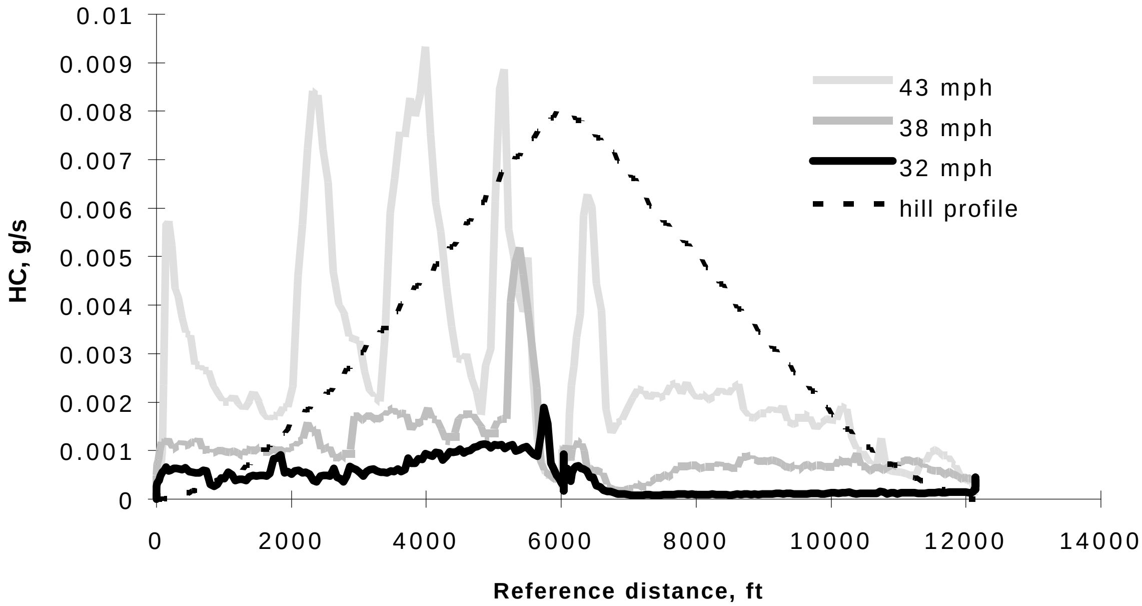


Figure 3. Hydrocarbons vs Time

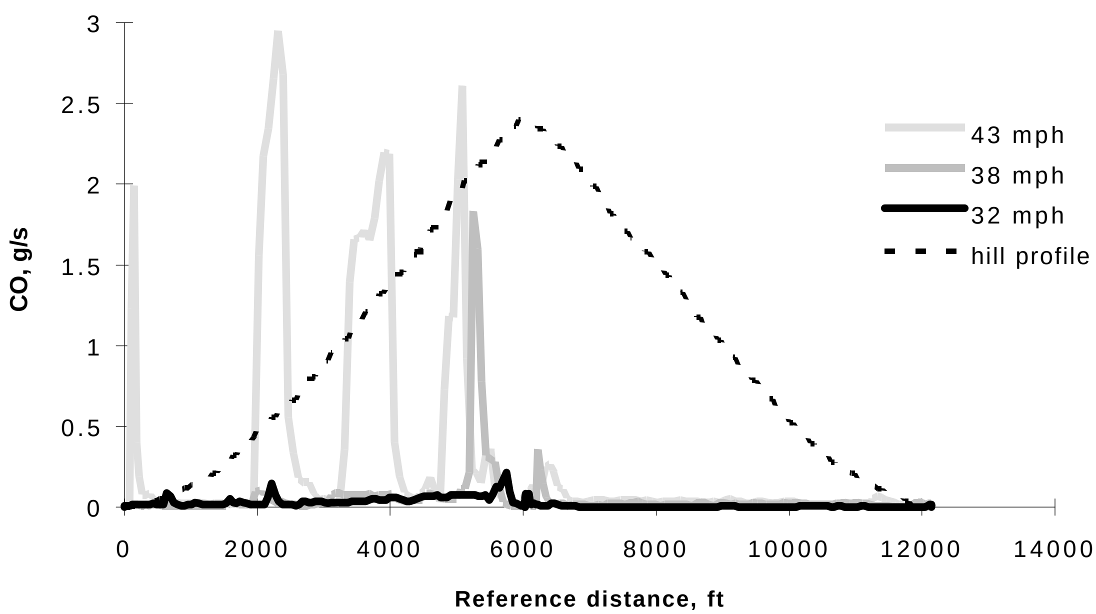


Figure 4. Carbon Monoxide vs Time

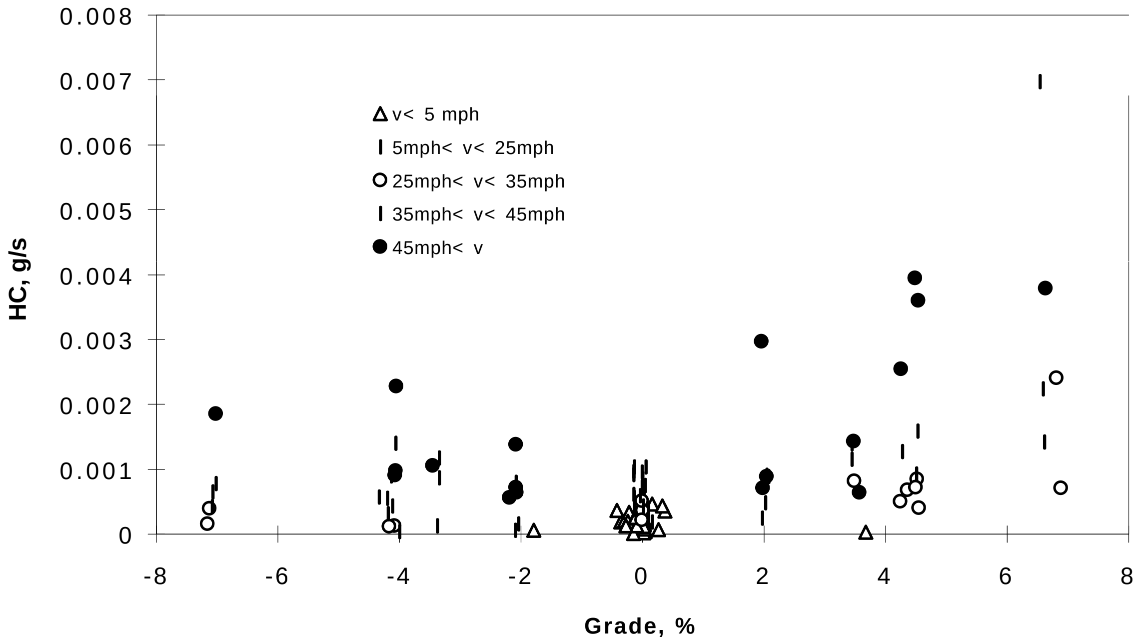


Figure 5. Hydrocarbons vs Grade

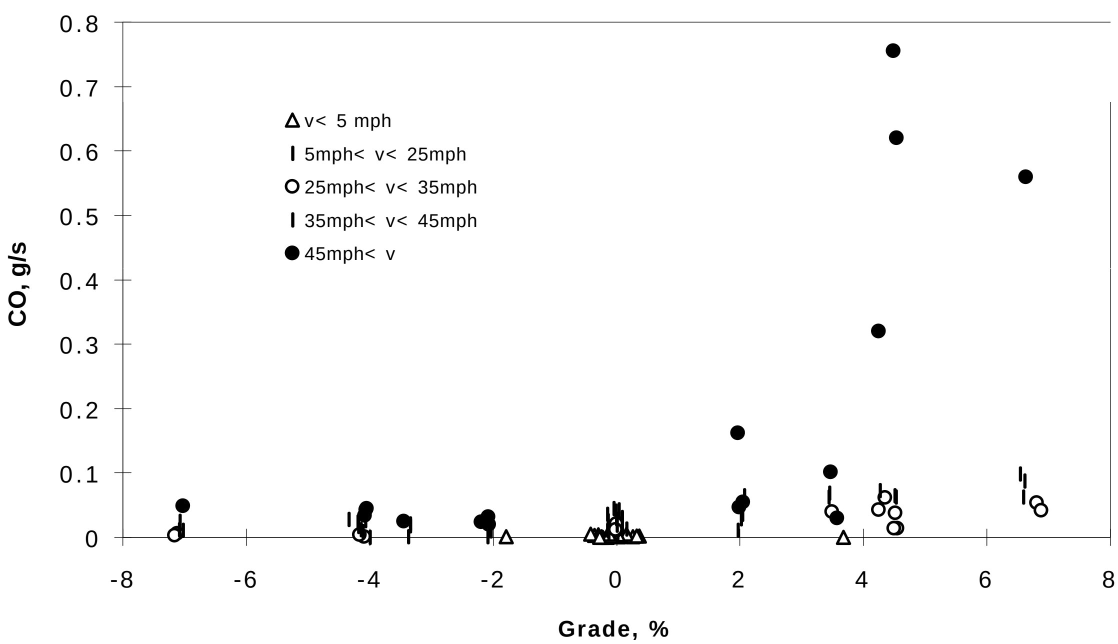


Figure 6. Carbon Monoxide vs Grade

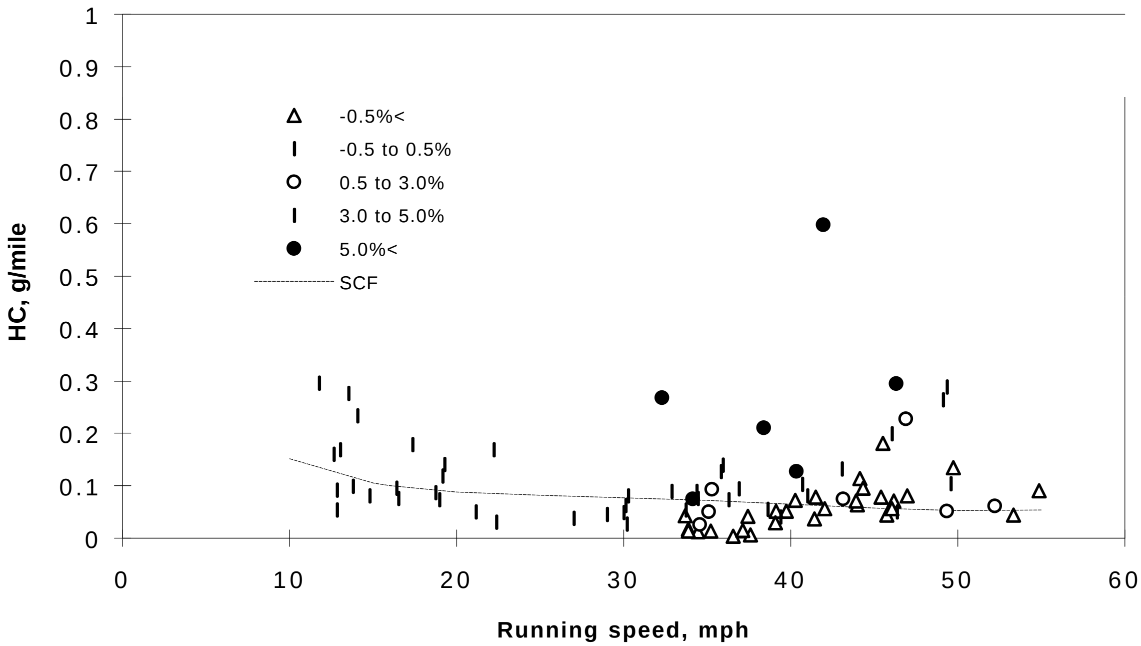


Figure 7. Hydrocarbons vs Speed

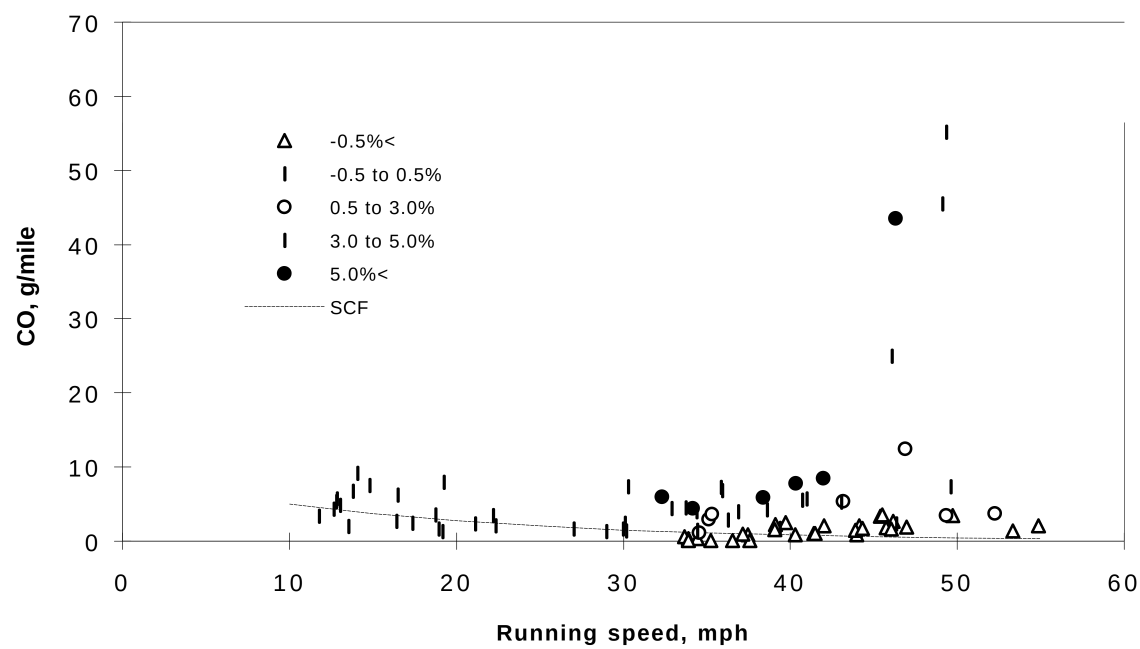


Figure 8. Carbon Monoxide vs Speed

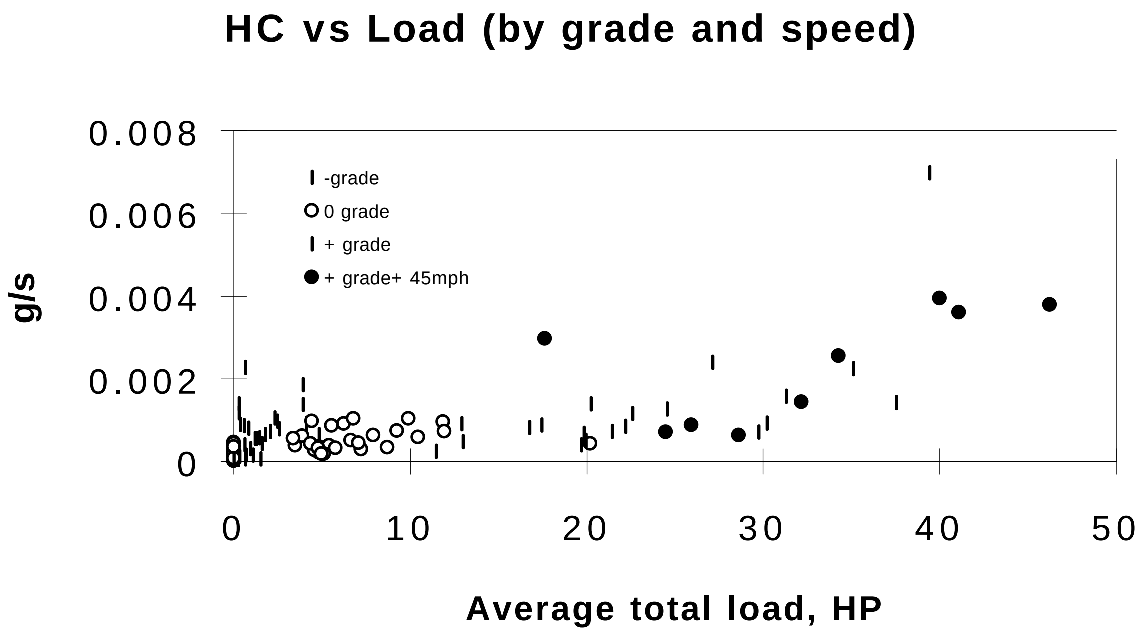


Figure 9. Hydrocarbons vs Load

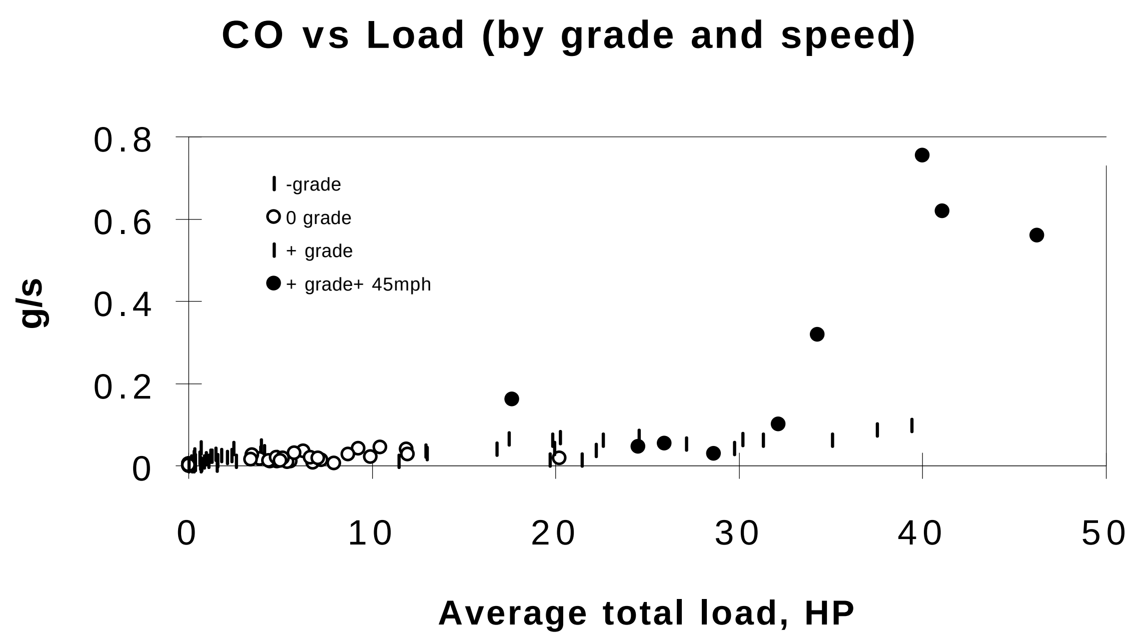


Figure 10. Carbon Monoxide vs Load